Effects of Temperature and Photoperiod on Development Rates of Nine Soybean Varieties in the Mississippi Valley

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Abstract

Time to flowering in soybeans *Glycine max* (L.) Merr. is affected by environmental conditions, temperature and photoperiod being the leading environmental factors. Most of available experimental data in the Mississippi Valley indicate mid- and late spring plantings. Planting dates in soybean crops vary significantly, and late plantings are not uncommon, especially in years with extreme spring weather events. The development rates of soybean are cultivar specific but also affected by temperature and photoperiod. The objective of this study was to quantify differences in development rates in field soybean crops encountering different daylength patterns. Nine soybean varieties were planted on three different dates in two soil types. Each treatment had five replications. Phenological observations and their quantitative analysis confirmed the earlier proposed hypothesis by Acock et al. (1997) that the daily increment in reproductive stage could be simulated as a linear function of photoperiod with slopes of these linear functions different before and after solstice.

INTRODUCTION

Soybean yields are highly sensitive to the length and timing of pod-filling period (Egli et al., 1984). Since Garner and Allard (1920) discovered photoperiodism, agricultural researchers made many attempts to account for photoperiodism when predicting the stages of reproductive development. To study the effects of management practices, soil properties and weather on the developmental rates, we need a reliable understanding of how environmental factors affect soybean ontogeny. Also, there is a need to predict growth stages for use in some irrigation-scheduling programs (Foroud et al., 1993; Specht et al., 1989). To quantify plant ontogeny means to define stages of development and to describe progress between the stages as a function of environmental factors (Acock et al., 1997). For soybean crops, the progress between stages is most often described as a continuous progression (Hodges and French, 1985; Summerfield et al., 1993; Sinclair et al., 1991). Summerfield et al. (1993) concluded that temperature and photoperiod are the leading factors in determining the rate of progress towards flowering. Photoperiod affects significantly on floral induction (Hicks, 1978). Several authors have also observed an effect of photoperiod on seed-filling rates (Grimm et al., 1994; Seddigh et al., 1989; Thomas and Raper, 1976), but some cultivars did not demonstrate this effect (Johnson et al., 1960). It has been also noticed that the rates of development depend on whether the daylength is increasing or decreasing (Constable and Rose, 1988; Lawn and Byth, 1972). The responses of soybean developmental rates to environmental factors are cultivar-specific (Constable and Rose, 1988; Grimm et al., 1994; Summerfield et al., 1993). The equations expressing these responses can be the same for several cultivars, but with different coefficients for each cultivar. These coefficients can be viewed as cultivar-specific parameters (Reddy et al., 1995). The southern USA is an important soybean growing region. During the period between 1991 and 1995, data on soybean growth and development were collected in the Mississippi Valley in seven southern states to validate the soybean crop simulator GLYCIM (Acock and Trent, 1991). These data could be used to quantify relationships between environmental variables and developmental rates for several soybean cultivars. The objective of this study was to quantify differences in

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developmental rates in field soybean crops encountering different daylength patterns.

MATERIAL AND METHODS

Plant Material

Data were collected in the fields of farmers collaborating in the testing of GLYCIM. The farmer decided what cultivars to grow. The permanently growing database is described in (Acock et al., 1997). In this study nine cultivars were analyzed. The cultivars DPL3478, DPL3588, DPL3640, DPL4344, DPL4909, DPL5354, DPL5655, DPL6200, and DPL6880 were grown on the Hood farm, 33.5^{o}N, -90.4^{o}W in 1999 each one on three sites on the Robinsonville sandy loam soil (Typic Udifluvents). The same nine cultivars were grown on Sharkey clay (Vertic Haplaquets) on the Hester farm in 1999, and DPL3588 on one site of Sharkey clay in 1997. The cultivar DPL3478 was grown in 1995 on two sites on the Hester farm, one was Bosket sandy loam (Typic Hapludalfs) and the second one was Dundee silty clay loam (Typic Endoaqualfs). It was also grown in 1997 on the McCain farm on Dubbs sandy loam soil. The data encompass a range of soil properties, weather conditions, planting dates, and irrigation schedules providing conditions from well watered to water stressed.

Reproductive Stages

The definitions of reproductive stages (R) are formulated by Fehr and Caviness, (1977). For analyzing developmental rates, Acock et al. (1997) supplemented this scheme by defining two additional stages: R(-1) = emergence, and R0 = floral initiation. In the initial scheme (Fehr and Caviness, 1977), R has only integer values. For the individual plant, therefore, the dependence of R both on time and on thermal units is stepwise. For crops, the value R has been defined as an average of values of R observed for 20 sample plants. This definition results in noninteger values of R for crops. The R-values presented in this study represent averages from 20 plants.

Determining the Pattern of Crop Reproductive Development

Phenological observations were conducted at intervals of one week or more, therefore, the time of the beginning of a particular crop stage was seldom known, and could be only estimated. Consequently, the rates of progress could not be calculated as the reciprocal difference between the times of beginning and ending of a stage (de Wit et al., 1970). To find rates of reproductive development, the graphs of R were plotted (1) against the number of the days after emergence, and (2) against thermal units for all data sets considered here, the same way as it is described in (Acock et al., 1997). Fig. 1 presents the rates of the reproductive development for three sites of DPL3478, as an example. The preliminary analysis of these graphs showed that (1) for a given observation date, no significant differences in R were found among crops of the same cultivar grown on different soils but with the same weather and type of irrigation, (2) plant population density did not affect R, (3) the segments of the graphs where R increased were approximately parallel for a given cultivar even in different conditions, (4) the time when R reached zero and the time to the end of the R2 plateau seemed to depend on the date of emergence, the time to the end of the R6 plateau did not correlate with the date of emergence. Acock et al. (1997) reported analogous observations for different soybean cultivars.

Quantifying Reproductive Developmental Rates

The procedure of quantifying developmental rates is described in detail by Acock et al. (1997). We used the same formula with the same set of parameters. The values of the parameters were determined for our data using the same procedure (see next paragraph). Data with R in the range between 0 and 2 were separated from other data for each cultivar in each data set. The following linear function was fitted to each of these subsets of data:

$$R = k_{0->2}(D - D_0) \quad [1]$$

where $k_{0->2}$ is the rate of progress per day from R0 to R2, D is the day of the year (DOY), and D_0 is the day of the year when the crop reaches R0. Data with R in the range between 2 and 6 were separated from other data for each cultivar in each data set. A piecewise linear function describing 'development-plateau-development' was fitted to these data. The equation of this function is:

$$R = \begin{cases} 2 + k_{0->2}(U - U_{2,end}), & 2 < R < 5 \\ 5, & U_{5,end} < U < U_{5,end} + \Delta_5 \\ 5 + k_{2->6}(U - U_{5,begin} - \Delta_5), & 5 < R < 6 \end{cases} \quad [2]$$

where $k_{2->6}$ is the rate of progress per degree-day from the end of R2 to the beginning of the R5 plateau and from the end of the R5 plateau to the start of R6; $U_{2,end}$ and $U_{5,begin}$ are the numbers of accumulated degree-days corresponding to the end of the R2 plateau and the beginning of the R5 plateau, respectively; and Δ_5 is the number of degree-days accumulated while the crop is on the R5 plateau. Thermal units were calculated from the average daily temperature (^oC), assuming a base temperature of 0^oC, see Acock et al. (1997). Then data with R in the range between 6 and 8 were separated from other data for each cultivar in each data set. The following piecewise linear function was fitted to these subsets of data:

$$R = \begin{cases} 6, & U_{6,begin} < U < U_{6,begin} + \Delta_6 \\ 6 + k_{6->8}(U - U_{6,begin} - \Delta_6, & U > U_{6,begin} + \Delta_6 \end{cases} \quad [3]$$

where $k_{6->8}$ is the rate of progress per degree-day from the end of R6 to R8, $U_{6,begin}$ is the number of accumulated degree-days when the average plant in the crop first reaches R6, and Δ_6 is the number of degree-days accumulated while the crop remains in R6. The value of $U_{6,begin}$ can be found from Eq. [2] by solving for R = 6:

$$U_{6,begin} = U_{5,end} + (1/ k_{2->6})$$

Therefore, only $k_{2->6}$ and Δ_6 need to be found by fitting Eq. [3] to the data. Having the standard errors of the parameters available allowed testing for significant differences between parameter values.

Fitting and Estimations

Average values of the parameters in Eq. [1], [2], and [3] were estimated by nonlinear minimization of the lack-of-fit mean square, s^2_r which is an unbiased estimator of the model's standard error (Pachepsky et al., 1996). The nonlinear minimization was also applied to finding parameter values in the equations expressing the dependencies of $D_{2,end}$ and D_0 on temperature and photoperiod. A modified Marquardt algorithm was used to obtain parameter values that minimized s^2_r in Eq. [4], and to estimate the standard errors of the parameters. We used the version of the algorithm published by Van Genuchten (1981). To assess the adequacy of the regression formulas, we employed criteria based on a statistical comparison of the lack-of-fit square s^2_r and the pure error mean square (Pachepsky et al., 1996).

RESULTS

Standard deviations of the observed values of R were between 0 and 0.8, with 90% of the values between 0.05 and 0.5 and with the median value close to 0.2. There was no significant decrease or increase in variability as the plants progressed through the reproductive stages.

To describe the progress towards flowering, we assumed that daylength is the significant factor and used a simple linear dependence of $f(P)$, a function of daily increment in R-stage on daylength P with different slopes before and after the summer solstice:

$$f(P_D) = \begin{cases} f_s + b_-(P_D - P_S), & D \le 173 \\ f_S + b_+(P_D - P_S), & D > 173 \end{cases} \qquad [4]$$

where f_s is the value of $f(P)$ at the summer solstice; P_D is the daylength; P_s is the daylength at the solstice; b_- and b_+ are the changes in $f(P)$ per hour change in daylength before and after the solstice, respectively. Table 1 presents the estimated values for the parameters in Eq 4.

Inspection of the data showed that the value of D_0 depended on emergence date. Studies by Garner and Allard (1930) and Johnson et al. (1960) also imply that as a first approximation, D_0 can be expressed as a linear function of the date of emergence, D_e:

$$D_0 = A + B\,D_e \qquad [5]$$

Combining Eq. [1] and [5], we obtain:

$$R = k_{0\text{->}2}\,(D - A - B\,D_e) \qquad [6]$$

This equation was fitted to the data, and values of $k_{0\text{->}2}$, A, and B were estimated (Table 2).

Table 3 presents the values of the parameters of the Eq. [2], as well as the values of the parameters c_1, the length of the plateau of the R6 with no stress, and c_2, the length of the plateau of the R6 as the stress increases for all cultivars.

DISCUSSION

The results show that the reproductive development of the soybean cultivars studied depends strongly on photoperiod and temperature. The error in the simple linear models that we used does not differ significantly from the error in the measurements. The small number of observations of reproductive development per crop prompted our use of linear models. Any nonlinear equations would have a larger number of coefficients than linear equations; therefore, the uncertainty in the values of these coefficients would be larger.

The selection of equations to simulate the effect of photoperiod on progress to flowering (R1) remains the subject of many discussions. For a given temperature, Grimm et al. (1994) and Summerfield et al. (1993) applied a piecewise linear dependence of progress to flowering on photoperiod. Sinclair et al. (1991) argued that the dependence is nonlinear and used a logistic formula. Summerfield et al. (1993) compared linear and nonlinear equations in predicting flowering and noted that linear equations were better suited for extrapolations. In the present study, the average photoperiod between emergence and floral induction was in the range of 13.8 to 14.4 h. The shape of the dependence could not be determined with certainty from this narrow range, therefore, we used a linear function [4]. Our goal was to determine a minimum set of parameters to define cultivar specific phenologies of soybean from field data. Data in Table 1 show that three parameters, three rates of progress, before, at, and after solstice, are the cultivar specific parameters which can be used in soybean crop simulations. Our earlier proposed hypothesis (Acock et al., 1997) that the daily increment in reproductive stage could be simulated as a linear function of photoperiod with slopes of these linear functions different before and after solstice (Table 1). This conclusion is supported by data from several authors (Acock and Trent, 1991; Garner and Allard, 1930, Jones and Laing, 1978). Some authors use the same function both before and after solstice (Summerfield et al., 1993), but Constable and Rose (1988) reported that using the same dependencies of development rate on photoperiod for early spring and early autumn planting failed to fit the data. Given the importance of predicting flowering in soybean, this issue demands further study.

The data used in this work show that the reproductive development of soybean crops includes several relatively long periods when the crops remain in the same stage (Fig. 1, Table 3). These plateaus have been observed before (e.g., Gertsis, 1985). The influence of water stress on the duration of seed filling (Table 3) has important implications for irrigation scheduling. Lengthening R6 with an appropriate irrigation may provide an increase in yield that more than pays for the irrigation. More elaborate studies and economic analysis are needed to see whether and how this kind of late-season irrigation can be used.

There are different data in the literature about the influence of the environmental factors on seed filling and maturity of soybean. In the present study, satisfactory results were obtained by assuming that post-flowering development is a function of thermal units accumulated after flowering (Table 3). The equations in this work do not use soil characteristics as environmental variables affecting reproductive development. We did not have enough data to identify soil parameters that might improve our predictions. However, since the length of the R6 plateau responds to the soil surface water balance (Table 3), soil water-holding capacity could be such a parameter. To test this possibility, the length of the R6 plateau would need to be defined with greater precision in experimental data.

Although the equations and the parameters values that we have developed and determined have limited regional applicability, the technique for their derivation based on the pattern of Fig. 1 may have a broader use. One possible application of our results is to use the equations in crop simulators. For this purpose, rates of development have to be used, rather than the reproductive development curves themselves. This technique may facilitate the application of crop simulators on farms by providing a set of parameters for reproductive development tailored to the cultivar being grown at a particular farm.

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Tables

Table 1. Parameters of the progress towards R0 for soybean cultivars studied, value ± standard error (SE) of parameter estimate.

Cultivar	Rate of progress towards RO at solstice, day^{-1}, intercept (f_s) in Eq. [4]	Rate of progress towards R0 before solstice, day-1, slope $b\_$ in Eq. [4]	Rate of progress towards R0 after solstice, day-1, slope b_+ in Eq. [4]
DPL3478	0.0328±0.0046	0.0080±0.0034	-0.0185±0.0064
DPL3588	0.0282±0.0012	0.0204±0.0013	-0.0199±0.0015
DPL3640	0.0192±0.0010	0.0143±0.0019	-0.0224±0.0017
DPL4344	0.0363±0.0013	0.0071±0.0023	-0.0206±0.0020
DPL4909	0.0308±0.0483	0.0100±0.0165	-0.0109±0.0247
DPL5354	0.0279±0.0014	0.0089±0.0009	-0.0187±0.0015
DPL5655	0.0262±0.0024	0.0110±0.0012	-0.0199±0.0016
DPL6200	0.0243±0.0016	0.0127±0.0006	-0.0279±0.0038
DPL6880	0.0208±0.0013	0.0119±0.0015	-0.0230±0.0026

Table 2. Parameters of the progress between R0 and R2, value ± SE as in Table 1.

Cultivar	Rate of progress from R0 towards R2, day^{-1}, $k_{0->2}$ in Eq. [6]	Intercept *A* of the Eq. [5] of R2 end on emergence date, day^{-1}	Slope *B* of the Eq. [5] of R2 end on emergence date, day^{-1}
DPL3478	0.249±0.410	112.8±1.7	0.603±0.011
DPL3588	0.090±0.020	130.9±2.2	0.560±0.014
DPL3640	0.158±0.031	153.6±2.8	0.460±0.019
DPL4344	0.199±0.065	105.5±2.7	0.641±0.017
DPL4909	0.165±0.129	106.4±3.4	0.648±0.017
DPL5354	0.121±0.026	116.1±6.7	0.616±±0.041
DPL5655	0.177±0.032	128.5±3.1	0.553±0.017
DPL6200	0.092±0.013	141.2±2.5	0.506±0.017
DPL6880	0.088±0.014	166.5±3.4	0.398±0.020

Table 3. Parameters of the progress from R2 towards R6, value ± SE as in Table 1.

Cultivar	Rate of progress from R2 towards R6 , $k_{0->2}$, day^{-1}, slope in Eq. [2]	Length of plateau R5, Δ_5, parameter in Eq. [2], dday	Length of plateau R5, c_1, dday, with no stress	Length of plateau R5, c_2, dday, as stress increases
DPL3478	0.0046±0.0002	40.9±2.4	588±20	1.14±0.03
DPL3588	0.0046±0.0001	44.0±1.6	624±15	1.07±0.03
DPL3640	0.0047±0.0001	76.6±2.5	581±14	0.78±0.03
DPL4344	0.0045±0.0001	41.3±1.9	502±17	1.16±0.05
DPL4909	0.0042±0.0002	57.7±3.4	569±17	0.80±0.03
DPL5354	0.0047±0.0002	47.4±1.6	611±35	1.09±0.07
DPL5655	0.0043±0.0002	44.5±2.2	554±28	1.18±0.05
DPL6200	0.0043±0.0001	53.7±4.5	625±29	1.03±0.03
DPL6880	0.0048±0.0002	49.3±1.5	560±39	1.20±0.00

<u>Figures</u>

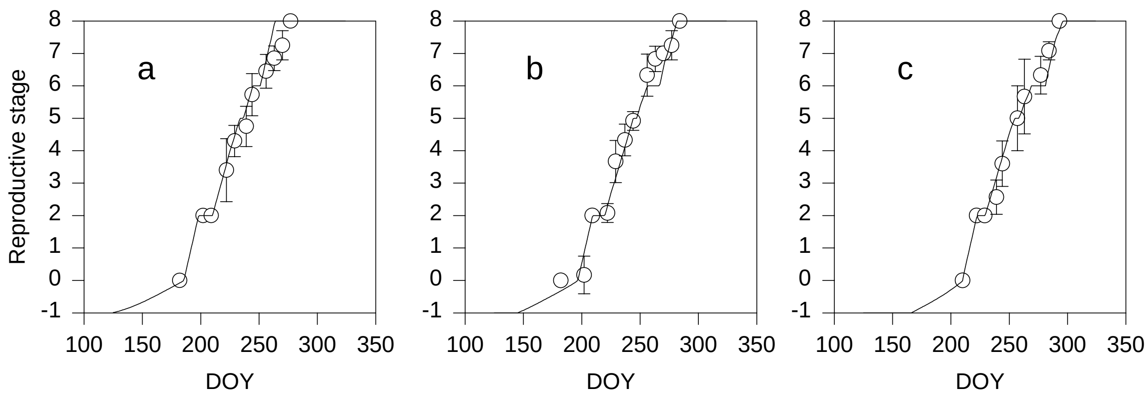

Fig. 1. Dependence of R-stage on time, measured (circles) and calculated (line) values for the cultivar DPL3478 at 3 different sites on the Hood farm in 1999 planted at different dates.